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Co-production of Hydrogen, Electricity and CO2 from Coal using Commercially-Ready Technology

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Large Scale Production of H_2 from Fossil Fuels

Four Related Papers Prepared Under Princeton University's Carbon Mitigation Initiative Presented Here

	Natural Gas	**Coal & Residuals**
CO_2 Venting	Almost all H_2 produced today	Refineries, chemicals, NH_3 production in China **2) "Conventional technology"**
CO_2 Capture	1) FTR vs. ATR with CC	**2) "Conventional technology"** 3) Membrane reactors 4) Overview

Motivation

- With respect to conventional Steam Cycles (SC), IGCC allow generating electricity from coal with:
  - higher efficiency
  - lower environmental impact
  - comparable costs
- Efficiency and cost penalties due to carbon capture are much lower for oxygen-blown IGCC than for SC
- Oxygen-blown IGCC with pre-combustion carbon capture produces fuel gas with ~93% H2 by volume
- An oxygen-blown IGCC with carbon capture can co-produce pure hydrogen with minimal modifications and very limited additional costs

Purpose of this study

- Understand thermodynamic and technological issues
- Assess performances and costs achievable with commercially available technologies
- Understand trade-offs among hydrogen, electricity and CO2 production
- Understand benefits/caveats of alternative configurations
- Build a reference for comparisons with alternative feedstocks (particularly nat gas) and advanced technologies (including membranes)

Basic Assumptions

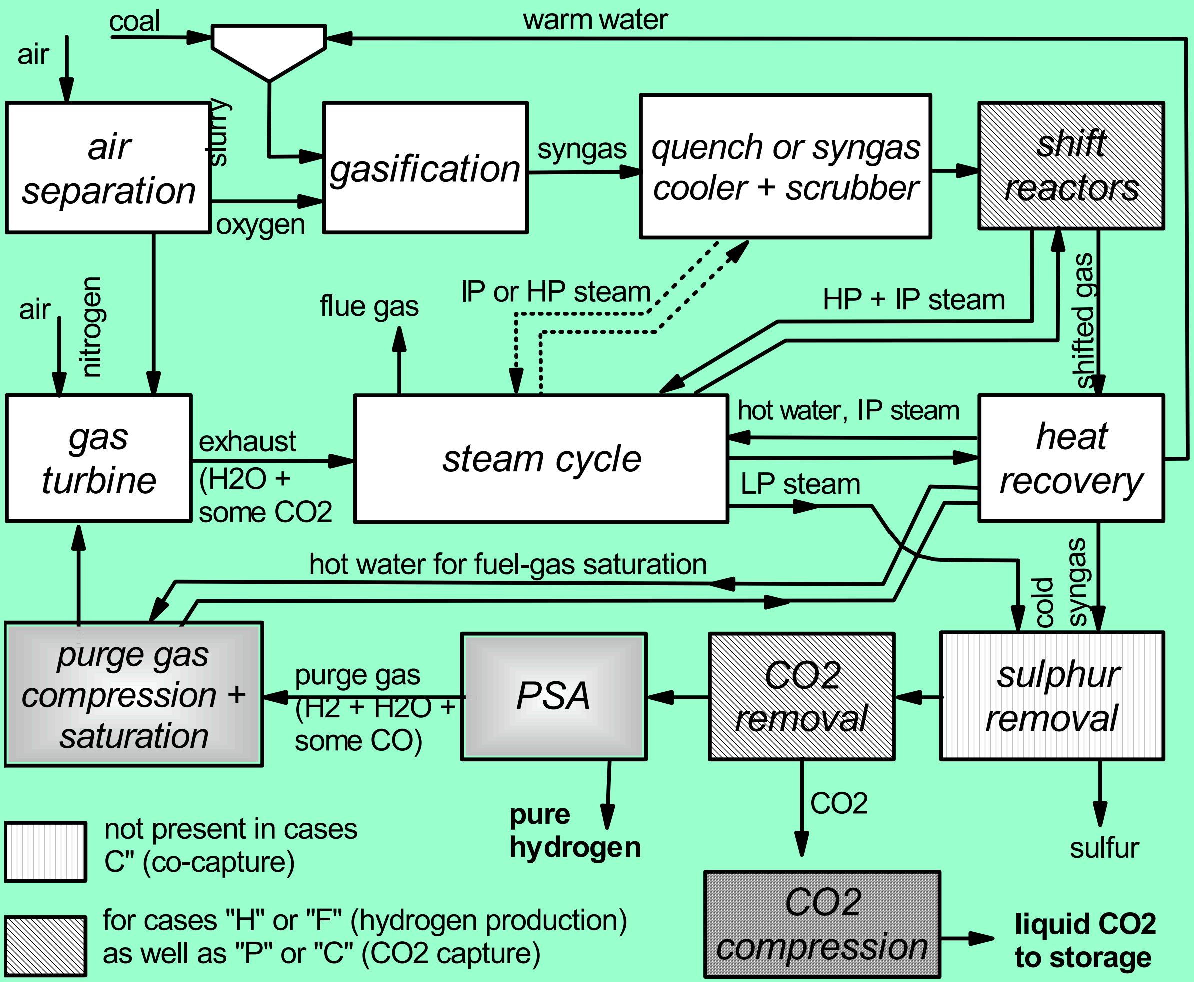
- Large scale plants: coal input 900-1800 MW (LHV), 1-2 large gasification trains
- Stand-alone plants: no steam or chemical integration with adjoining process
- Texaco gasifier at 70 bar with (i) quench or (ii) radiative + convective syngas cooler
- Current "F" gas turbine technology: Siemens V94.3a for plants producing mainly electricity, Siemens V64.3a for plants producing mainly hydrogen
- CO2 venting vs CO2 capture by physical absorption (Selexol)
- Pure H2 separated by Pressure Swing Absorption (PSA)

Plant configurations

- 1) Production of Electricity vs H_2
- 2) CO_2 venting vs CO_2 capture
- 3) Quench vs Syngas cooler

Power Cycle	Main Output	CO2 venting		CO2 capture	
		quench	syngas cooler	quench	syngas cooler
Combined Cycle	Electricity	1 case	1 case	1 case	1 case
	Hydrogen	1 case	1 case	investigate: a) gasif pressure b) H2S+CO2 co-capture c) H2 purity d) E/H2 ratio	investigate: a) steam/carbon b) E/H2 ratio
Steam Cycle	Hydrogen	assess performances and costs vs IGCC		assess performances and costs vs IGCC	

Basic system design



not present in cases C" (co-capture)

for cases "H" or "F" (hydrogen production) as well as "P" or "C" (CO2 capture)

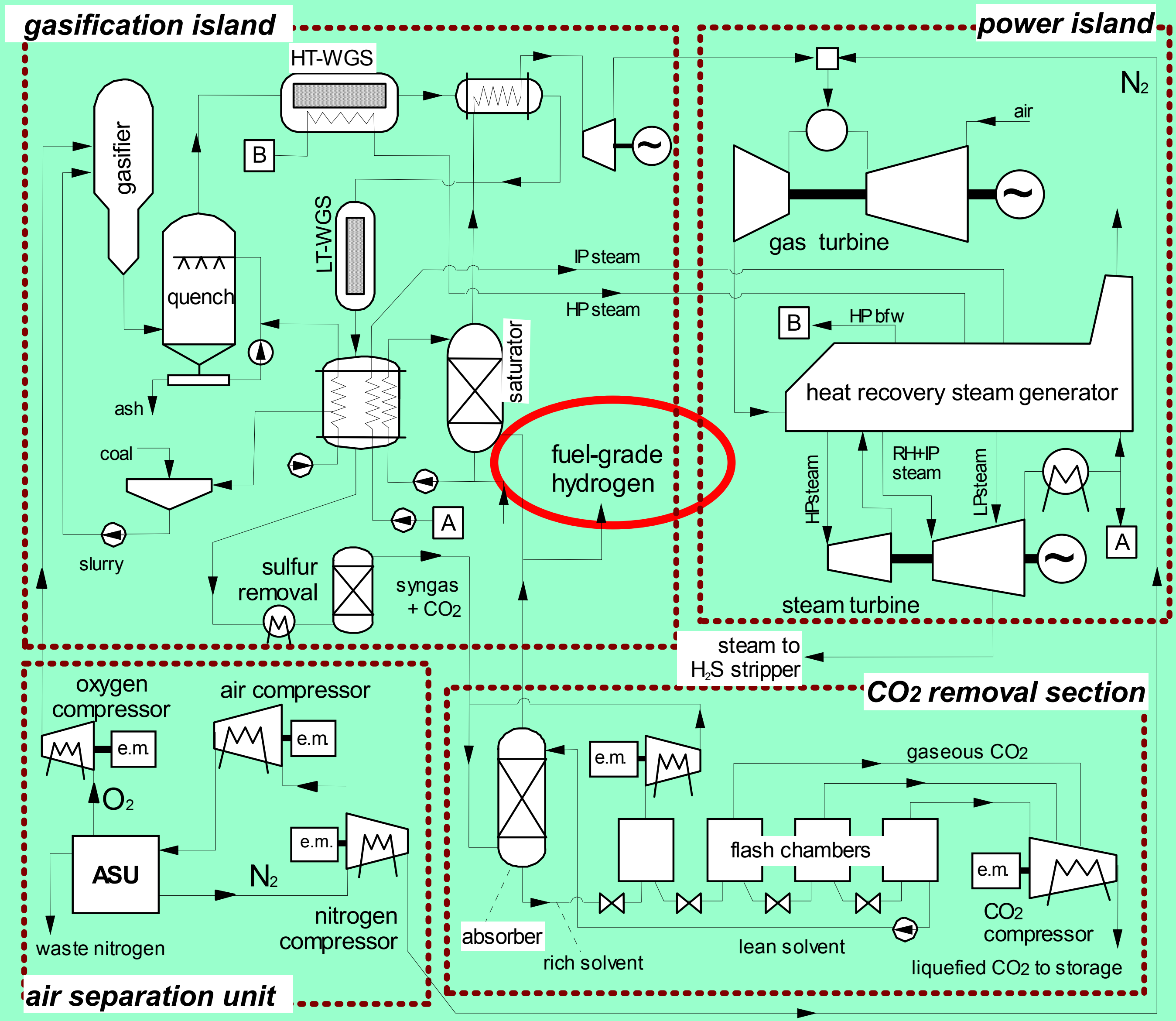
for cases "P" (capture pure CO2) as well as "C" (co-capture)

for cases "H" (pure H2), otherwise substtuted by **saturator and syngas expander**

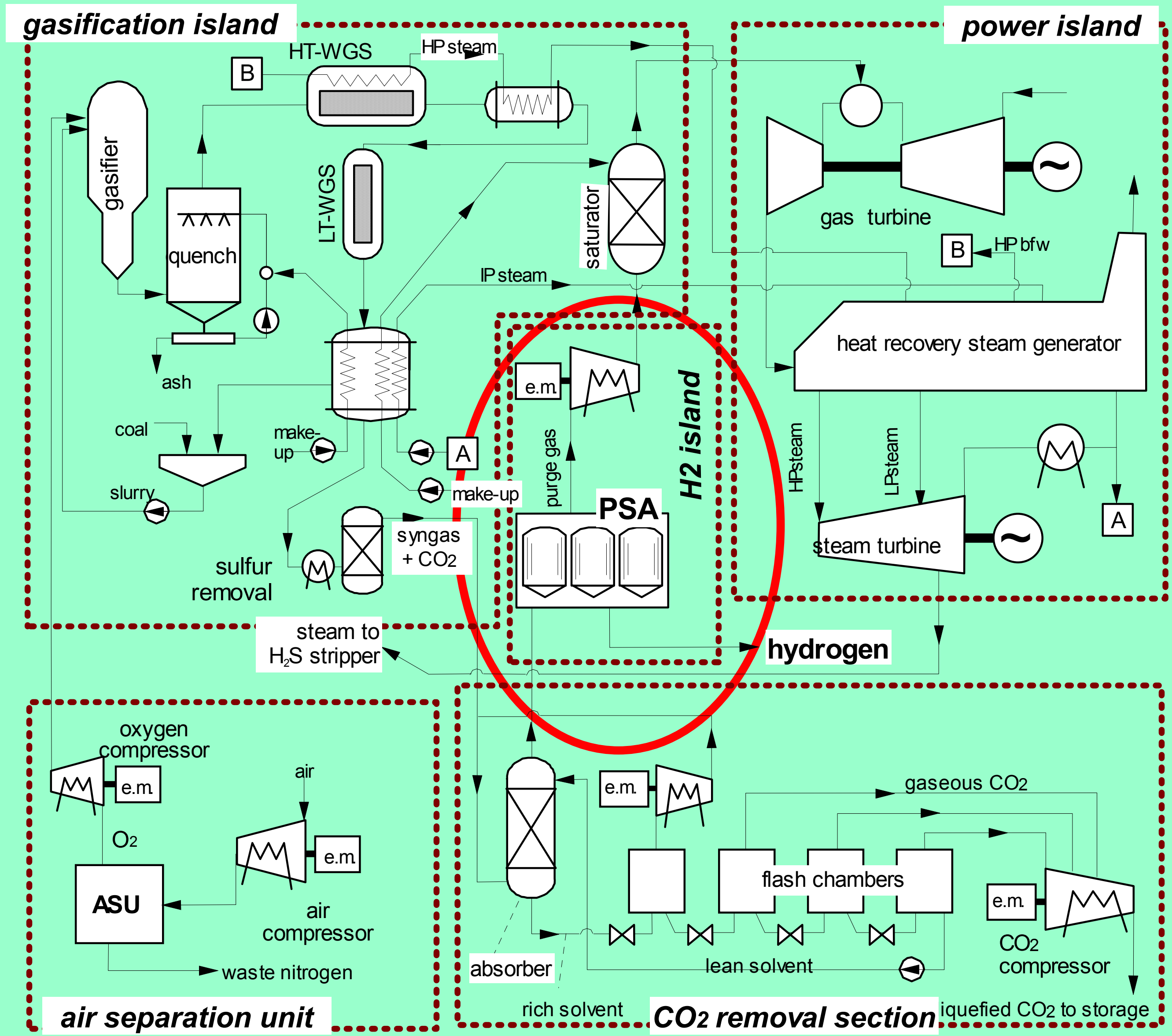
More Basic Assumptions

- 95% pure O_2 compressed at 84 bar. N_2 compressed to gas turbine combustor for NOx control (Tstoich ≤ 2300 K)
- Sulfur removal by physical absorption (Selexol) with steam stripping + Claus plant + SCOT unit
- Tight integration with steam cycle with 4 pressure levels. Evaporation at 165, 15, 4 bar; Reheat at 36 bar. Superheat and Reheat at 565°C
- With CO_2 capture, HT shift at 400-450°C + LT shift at 200-250°C. Both ahead of sulfur removal.
- Air flow to gas turbine adjusted to keep same pressure ratio of nat gas-fired version
- CO_2 released in 3 flash tanks at decreasing pressure to minimize compression work (+ 1 HP flash and recycle compressor to minimize H_2 co-capture)

Electricity-Pure CO2 capture-Quench



Hydrogen-Pure CO2 capture-Quench



Heat and Mass Balances

- Code developed at Politecnico di Milano and Princeton to predict the performances of power cycles, including:
  - chemical reactions (→ gasification, steam reforming)
  - heat/mass transfer (→ saturation)
  - some distillation process (→ cryogenic Air Separation)
- Model accounts for most relevant factors affecting cycle performance:
  - scale
  - gas turbine cooling
  - turbomachinery similarity parameters
  - chemical conversion efficiencies
- Accuracy of performance estimates has been verified for a number of state-of-the-art technologies

Capital Cost Estimate

$$Cost\ (M\$) = n \cdot C_0 \cdot [S/(n \cdot S_0)]^f$$

Component	*Scaling parameter*	*Cost model*	*Base cost C0 M$*	*Base Size S0*	*scale factor f*	*# of Trains n*
Coal stoarge, prep, handling	Raw coal feed (mt/day)	Holt-e	29.1	2367	0.67	2/1
Air separation unit	Pure O2 input (mt/day)	Holt-e	45.7	1839	0.50	2/1
Extra O2 compressor	% of total O2 comp. pwr (MWe)	Lozza	6.3	10.0	0.67	2/1
N2 compressor (for GT NOx control)	N2 compression power (MWe)	Lozza	4.7	10.0	0.67	2/1
Gasifier + quench cooling/scrub	Coal input (MWth, HHV)	Holt-e	61.9	716	0.67	2/1
Gasifier + syngas cooler & scrub	Coal input (MWth, HHV)	Holt-e	144.3	734	0.67	2/1
WGS reactors, heat exchangers	Coal input (MWth, HHV)	Lozza	39.8	1450	0.67	2/1
Selexol H2S removal & stripping *	Sulfur flow (mt/day)	Holt-e	33.6	80.7	0.67	2/1
Sulfur recovery (Claus, SCOT) **	Sulfur flow (mt/day)	Holt-e	22.9	80.7	0.67	2/1
Selexol CO2 absorption, stripping	Pure CO2 flow (mt/hr)	Lozza	32.8	327.3	0.67	2/1
CO2 drying and compression	CO2 compression pwr (MWe)	Jacobs	14.8	13.2	0.67	2/1
Pressure swing adsorption	Purge gas flow (kmole/s)	Jacobs2	7.1	0.2942	0.74	2/1
PSA purge gas compressor	Purge gas comp power (MWe)	Lozza	6.3	10.0	0.67	2/1
Syngas expander	Syngas expander pwr (MWe)	Lozza	3.1	10.0	0.67	2/1
Siemens V64.3A gas turbine	Gas turbine power (MWe)	GTW	30.6	67.1	-	1/0
Siemens V94.3A gas turbine	Gas turbine power (MWe)	GTW	74.9	265.9	-	0/1
GE Frame 7H gas turbine	Gas turbine power (MWe)	GTW	92.1	345.4	-	0/1
HRSG and steam turbine	ST gross power (MWe)	Lozza	94.7	200.0	0.67	1
Power island BOP+electrics	GT+ST gross power (MWe)	Lozza	57.6	450.0	0.67	1

Estimate Cost of Electricity and Cost of H_2

Economic parameters:	
Construction interest (% of OC)	16%
Capital charge rate (%/yr)	15%
Capacity factor (%)	80%
O&M costs (% of OC per year)	4%
Coal price ($/GJ, LHV)	1.24
CO_2 disposal cost ($/t$CO_2$)	5.00
Value of Sulfur	0.00
Extra-cost for CO_2+H_2S co-sequestration	0.00
All costs in 2002 US $	

For plants producing H_2, value electricity at the cost of the configuration with the same identical features (quench vs syncooler, venting vs capture, etc.)

Plants producing only electricity

		no CO2 capture		CO2 capture	
		quench	syncooler	quench	syncooler
% of coal input	Gas turbine	32.41	32.46	29.86	30.02
	Steam turbine	19.67	23.04	18.22	20.36
	Syngas expander	1.04	1.08	1.00	1.02
	ASU and gas compression	-8.41	-8.12	-7.64	-7.53
	Auxiliaries	-1.76	-1.83	-1.75	-1.86
	CO2 removal and compression	0.00	0.00	-2.91	-2.89
	Net electric output	**42.95**	**46.63**	**36.79**	**39.12**
	Total Cost, $/kWe	1395	1586	1808	2038
c/kWh	Capital (15% of TCR)	2.99	3.39	3.87	4.36
	O&M costs (4% of OC per year)	0.69	0.78	0.89	1.00
	Fuel (at 1.24 $/GJ, LHV)	1.04	0.96	1.22	1.15
	Total electricity cost	**4.72**	**5.14**	**5.98**	**6.51**
	CO2 Capture cost, $/mt CO2	**-**	**-**	**18.53**	**22.27**
	Extra c/kWh for disposal at 5 $/mt CO2	-	-	0.40	0.38

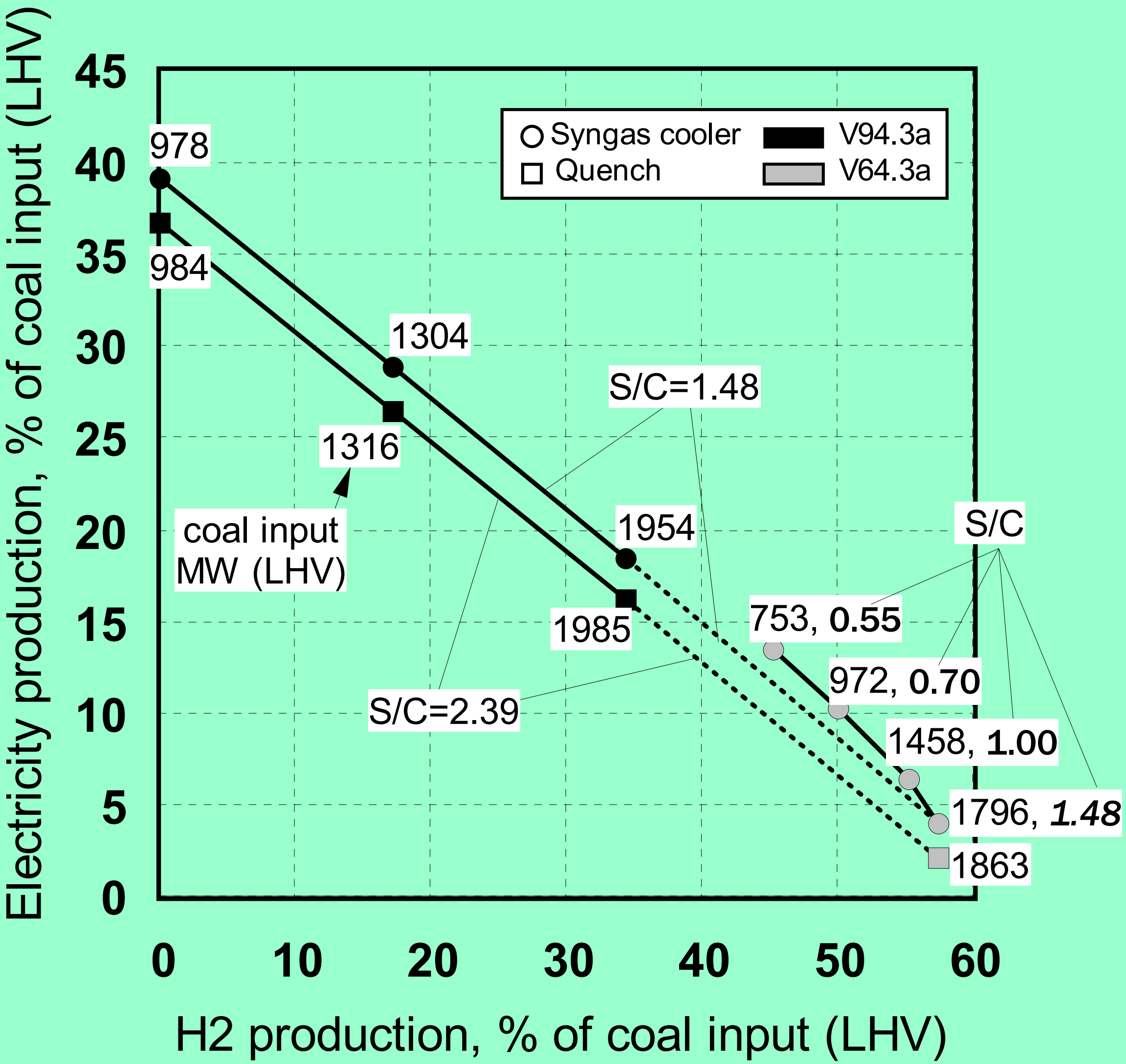
Plants producing mainly hydrogen

		no CO2 capture		CO2 capture	
		quench	syncooler	quench	syncooler
% of coal LHV input	Gas turbine	4.23	4.51	4.23	4.51
	Steam turbine	7.49	9.38	7.49	9.38
	Syngas expander	0.00	0.00	0.00	0.00
	ASU and gas compression	-5.37	-5.39	-5.37	-5.39
	Auxiliaries	-1.32	-1.49	-1.36	-1.49
	CO2 removal and compression	-0.82	-0.82	-2.91	-2.89
	Net electric output	**4.21**	**6.18**	**2.09**	**4.11**
	Net hydrogen output	**57.46**	**57.45**	**57.46**	**57.45**
	Total Cost, $/kW H2 LHV	830	1076	874	1124
$/GJ LHV	Capital (15% of TCR)	4.93	6.40	5.20	6.69
	O&M costs (4% of OC per year)	1.13	1.47	1.19	1.54
	Fuel (at 1.24 $/GJ, LHV)	2.17	2.17	2.17	2.17
	Electricity revenue (4.72/6.38 c/kWh)	-0.96	-1.41	-0.64	-1.27
	Total hydrogen cost	7.28	8.63	7.92	9.12
	Extra $/GJ for disposal at 5 $/mt CO2	-	-	0.72	0.70

Other configurations

		Base quench, 70 bar S removal 99+ purity max H2	gasifier at 120 bar	co-capture of H2S and CO2	fuel-grade purity	increase E/H2 by reducing flow to PSA
% of coal LHV input	Gas turbine	4.23	4.33	4.23	3.91	22.31
	Steam turbine	7.49	6.62	7.49	7.25	15.03
	Syngas expander	0.00	1.71	0.00	0.18	0.73
	ASU and gas compression	-5.37	-5.56	-5.37	-4.98	-6.97
	Auxiliaries	-1.36	-1.40	-1.36	-1.40	-1.64
	CO2 removal and compression	-2.91	-2.90	-2.91	-2.91	-2.91
	Net electric output	**2.09**	**2.80**	**2.09**	**2.06**	**26.56**
	Net hydrogen output	**57.46**	**57.28**	**57.46**	**58.17**	**17.25**
	Total Cost, $/kW H2 LHV	874	885	773	834	-
$/GJ LHV	Capital (15% of TCR)	5.20	5.26	4.60	4.96	-
	O&M costs (4% of OC per year)	1.19	1.21	1.06	1.14	-
	Fuel (at 1.24 $/GJ, LHV)	2.17	2.18	2.17	2.15	-
	Electricity revenue (4.72/6.38 c/kWh)	-0.64	-0.87	-0.60	-0.63	-
	Total hydrogen cost	**7.92**	**7.78**	**7.22**	**7.62**	**-**
	Extra $/GJ for disposal at 5 $/mt CO2	0.72	0.72	0.72	0.71	-

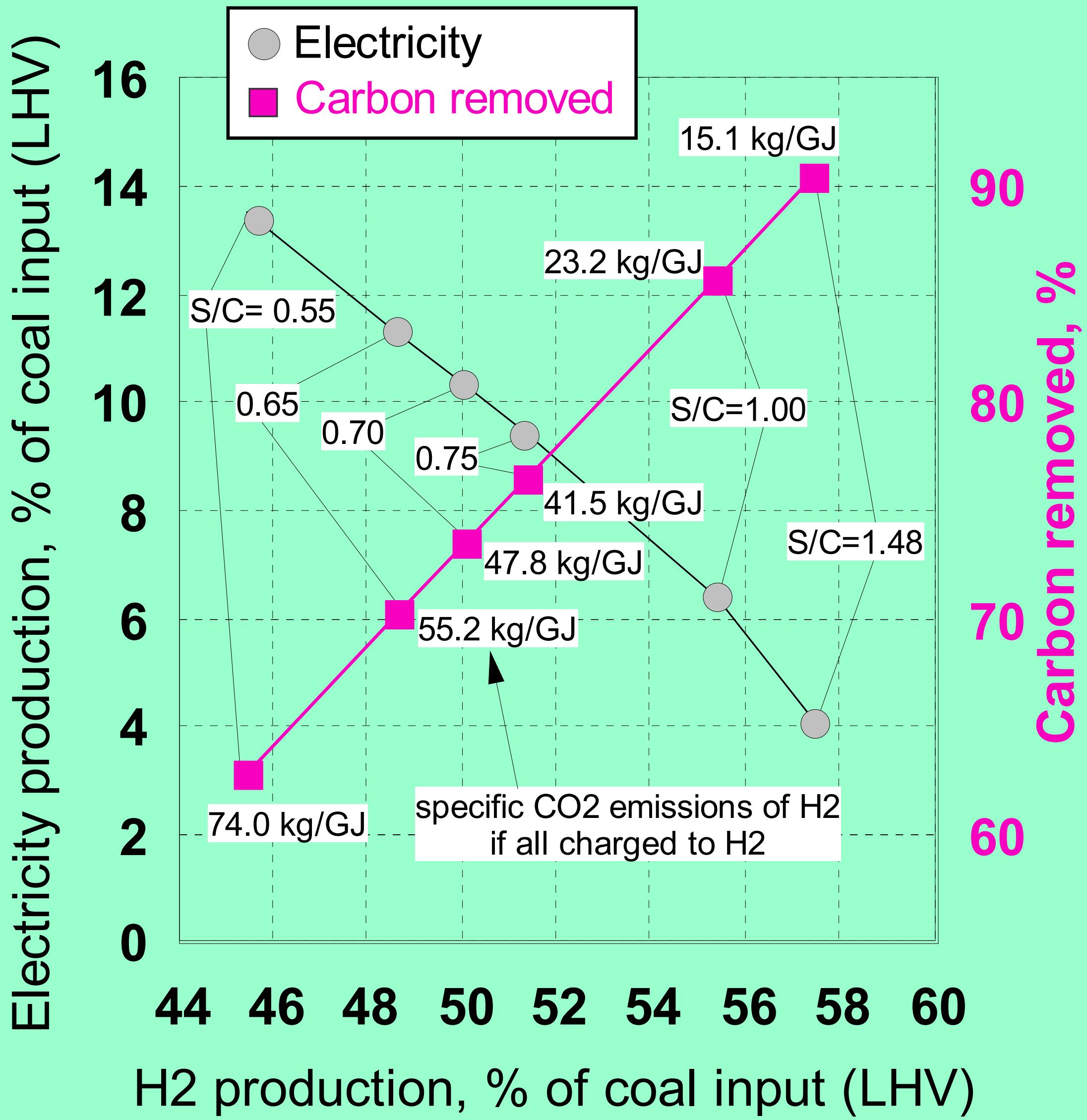
Results
Varying Electricity/H2 ratio



At constant S/C:
$\Delta E/\Delta H$ = ~ 59.5 %

With syngas cooler, can decrease S/C and get $\Delta E/\Delta H$ ~ 70% at the expense of higher CO_2 emissions

Configurations with syngas cooler
trade-off between electricity and CO2 emissions



Conclusions

- The production of de-carbonized electricity or hydrogen from coal via oxygen-blown IGCC requires essentially the same plant configuration
- Such plant can operate with Electricity/H2 ratios spanning the whole range from about zero to ∞
- De-carbonized H2 can be traded off de-carbonized Electricity at an efficiency of ~ 60% for all configurations. In configurations with syngas cooler, efficiencies ~70% can be achieved at the expense of higher CO2 emissions
- At CO2 disposal costs of 5 $/t CO2, cost of de-carbonized H2 is in the range 8.5-10 $/GJ LHV
- Cost of avoided CO2 from coal-to-H2 plants can be as low as 5-10 $/t CO2. Then must add disposal cost

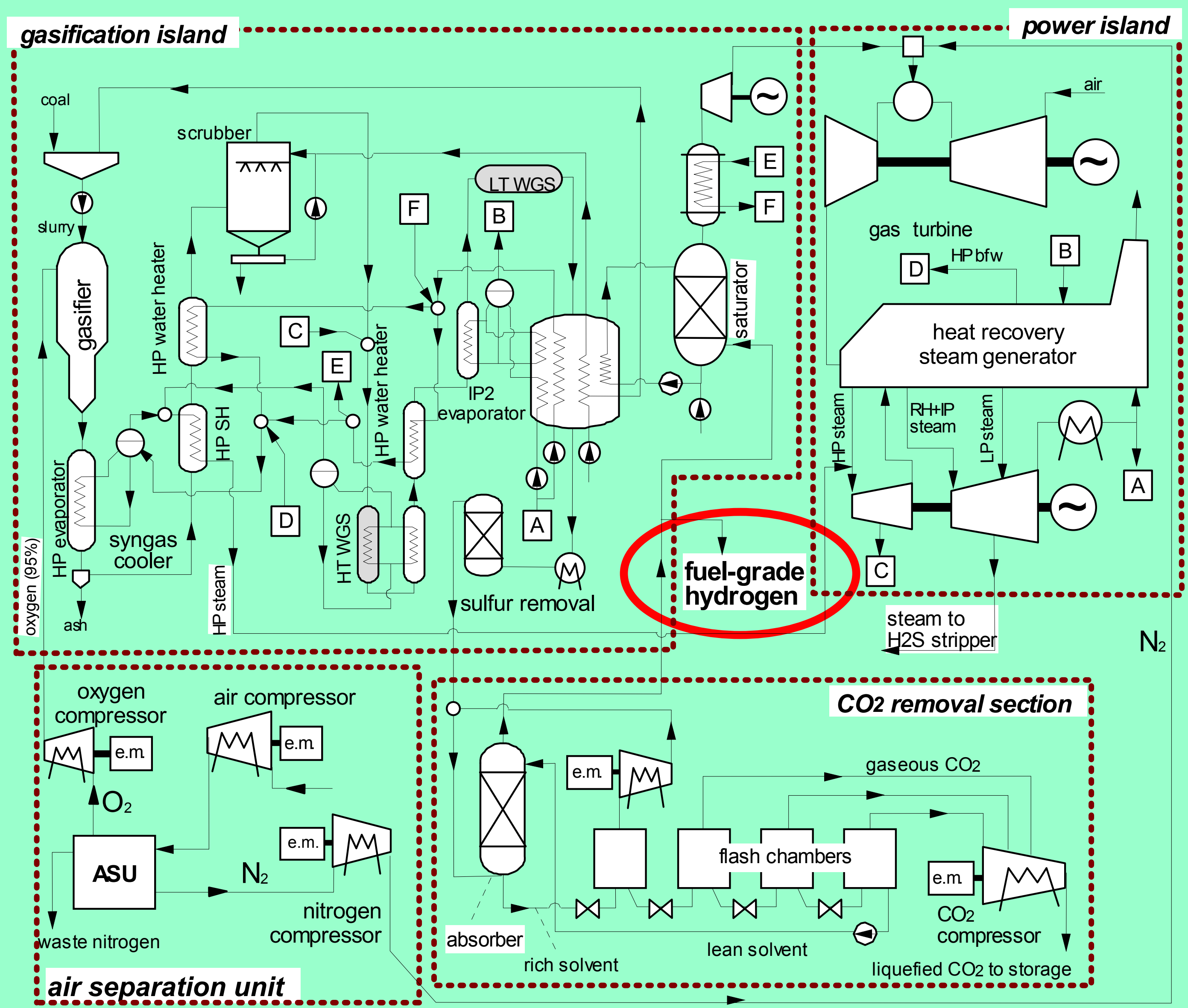
More Conclusions

- Energy efficiency advantage of syngas cooler configurations vanishes as ratio E/H2 decreases
- The costs of current water-tube syngas cooler designs make them unattractive for electricity and (even more) for H2 production
- Co-capture of CO2 and H2S appears to have the same cost of sulfur removal alone. If that's confirmed, co-capture allows capturing CO2 at almost zero cost.
- Increasing gasification pressure from 70 to 120 bar does not seem to give significant advantages
- "Fuel-grade" H2 vs pure H2 increases electric efficiency by ~1 percentage point and decreases H2 cost by ~4%

Assumptions

COAL HANDLING, GASIFIER and ASU		STEAM CYCLE	
Power for coal handling, % of coal LHV	1	Steam evaporation pressures, bar	165, 36, 15, 4
Water/solids ratio in slurry	0.333	Steam temperature at admission, °C	565
Gasification pressure, bar	70	Condensation pressure, bar	0.04
Syngas temperature at gasifier exit, °C	1327	HRSG gas side pressure losses, kPa	3
Heat losses in gasifier, % of input LHV	0.5	Pinch point ΔT, °C	8
ASU power consumption, $kJ_{el}/kg_{PURE}\ O_2$	918.9	Minimum ΔT in SH and RH, °C	25
O_2 purity, % vol.	95	Deaerator pressure, bar	1.4
Pressure of O_2 and N_2 delivered by ASU, bar	1.01	Power for heat rejection, % of heat discharged	1
Pressure of O_2 to gasifier, bar	84	Hydraulic efficiency of pumps, %	0.75
Temperature of O_2 to gasifier, °C	200	Organic/electric efficiency of motor drives	0.94
QUENCH OR SYNGAS COOLER		SULFUR REMOVAL (Physical Absorption)	
Pressure losses, %	2	Temperature of absorption tower, °C	35
Syngas loss (accounts for unconverted carbon), %	0.8	Syngas pressure loss, %	1
Ash discharge temperature (for syn-cooler), °C	350	Moles of CO_2 removed per Mole of H_2S	2
Blowdown (for quench), %	2	Net steam consumption, MJ 5 bar steam /kgS	5
HEAT EXCHANGERS		CO_2 REMOVAL (Physical Absorption)	
Pressure loss, %	2	Temperature of absorption tower, °C	35
Minimum ΔT for gas-liquid heat transfer, °C	10	Syngas pressure loss, %	1
Pinch point ΔT for evaporators, °C	8	Pressure of last (4th) flash drum, bar	1.05
Heat losses, % of heat transferred	0.7		
WATER-GAS SHIFT REACTORS		SYNGAS EXPANDER/COMPRESSOR	
Pressure loss, %	4	Polytropic efficiency of syngas expander, %	88
Temperature at exit of HT reactor, °C	400	Polytropic efficiency of syngas compressor, %	85
Temperature at inlet of LT reactor, °C	200	Pressure of syngas to GT combustor pressure	1.5
		CO_2 COMPRESSOR	
		Final delivery pressure, bar	150
		Compressor adiabatic efficiency, %	82
		Final pump efficiency, %	75
		Temperature at inter-cooler exit, °C	35
		Pressure drops inter-cooler and dryer, %	1
		# of inter-coolers set maintain CO_2 below 200°C	

Electricity-Pure CO2 capture-Syngas cooler



Other configurations

- Plants with no gas turbine give higher hydrogen production, but the significant reduction of electricity production makes them unattractive
- If fuel-grade (~93% pure) hydrogen is acceptable, H2 production increases by 0.7 percentage point and hydrogen cost decreases by ~4%
- In schemes with syngas cooler, Electricity/H2 ratio and overall efficiency can be increased, at the expense of higher CO2 emissions, by lowering the steam/carbon ratio
- Increasing gasification pressure to 120 bar improves efficiency of configurations with quench, while those with syngas cooler are almost unaffected. Impact on hydrogen cost is marginal